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## Article

# The dark and bright side of network complexity: Novel insights from an asymmetric supply chain recovery and disruption approach

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## OPERATIONS, INFORMATION & TECHNOLOGY | RESEARCH ARTICLE

# The dark and bright side of network complexity: Novel insights from an asymmetric supply chain recovery and disruption approach

Emmanuel Asafo-Adjei<sup>1</sup>, Zulaiha Hamidu<sup>2</sup>, Kassimu Issau<sup>2\*</sup>, Baba Adibura Seidu<sup>3</sup> and Anokye M. Adam<sup>1</sup>

**Abstract:** Recent studies have conceptualized the potential for a dark and bright perspective of network complexity in relation to supply chain disruption and resilience respectively. Few empirical studies have been conducted on the relationship among supply chain network complexity, supply chain disruption and supply chain resilience. However, prior studies have not yet investigated how different measures of network complexity relate to both resilience strategies and disruption. The current study, therefore, examines the dark and bright side of supply chain network complexity dimensions using supply chain disruption (SCD) and three supply chain resilience (SCR) strategies (collaboration, flexibility and redundancy) as endogenous variables. The dimensions of the supply chain network complexity utilised in this study are—supply complexity (SNC), customer complexity (CNC), and logistics complexity (LNC) whereas the three SCR strategies considered included; collaboration, flexibility and redundancy. The study uses PLS-SEM and a sample of 690 manufacturing firms in Accra Metropolis. Results show that supply complexity has a positive relationship with both disruption and resilience strategies, while customer complexity is only related to disruption, and logistics complexity is related to all resilience strategies. The study provides theoretical, practical, and political implications.

**Subjects:** Operations Management; Supply Chain Management; Organizational Studies

**Keywords:** Supply complexity, customer complexity; logistics complexity; supply chain resilience; supply chain disruption; asymmetric approach

## 1. Introduction

The current study addresses concerns relating to the dark and bright side of supply chain network complexity in relation to supply chain resilience and disruption. The unexpected supply chain disruptions have become more frequent and severe in recent years, which indicates that the global business environment is still changing (Cao et al., 2022; Modgil et al., 2021). The mismatch between supply and demand that can have an impact on a company's short- and long-term operations, as well as its profitability, is known as a supply chain disruption (Birkie et al., 2017). Company performance can be severely harmed by supply chain disruptions. Following the 2011 tsunami in Japan, Toyota experienced a supply network disruption. Owing to a shortage of parts, Toyota had to shut down some of its North American factories six months later (Kim et al., 2015).

The current state of supply chain disruption and resilience is still evolving due to ongoing global events such as the COVID-19 pandemic, geopolitical tensions, natural disasters, and other factors that continue to impact global trade and supply chains (Dwaikat et al., 2022; Hamidu et al., 2022, 2023; Trabucco & De Giovanni, 2021; Umar et al., 2022; Zighan & Ruel, 2023; Zighan et al., 2022). In general, supply chain disruptions have increased in frequency and severity over the past few years, and the COVID-19 pandemic has exposed many vulnerabilities and weaknesses in global supply chains (Hamidu et al., 2023). Some of the key challenges that companies face include shortages of raw materials, transportation delays, border closures, labor shortages, and increased costs for logistics and shipping.

Despite these challenges, many companies are investing in strategies to build more resilient supply chains. This includes diversifying suppliers and manufacturing locations, increasing visibility and transparency in supply chains, adopting new technologies such as blockchain and automation, and creating contingency plans for different types of disruptions. Overall, while the current state of supply chain disruption and resilience remains challenging, many companies are taking proactive steps to mitigate risks and build more resilient supply chains for the future.

In this regard, studies have mostly examined how vulnerable organisations are and/or what tools they require to control those weaknesses (Berkas, 2007; Cao et al., 2022; Gharaei, Amjadian, et al., 2023; Wang et al., 2018). However, Kim et al. (2015) assert that supply disruptions (i.e., cessations of material flows) frequently occur from a focus firm's network complexity relating to supply, customer and logistics. Additionally, network level failures are not always the result of local level disturbances. This is because from the general systems theory, supply chain network is seen as complex with many internal and external components, the success or failure of a system is determined by the interaction of the system's various internal and exterior features (Bertalanffy, 1968; Dey, 2016). As a result, a company's inability to handle supply disruptions frequently results from a lack of knowledge of the supply network. Companies strive to develop resilience so they can endure and recover from such disturbances (Wiedmer et al., 2021).

According to a number of recent research, resilience skills aid businesses in regaining lost performance as a result of disruption (Cerchione et al., 2020; Lusiantoro & Pradiptyo, 2022; Marcucci et al., 2021; Mubarik et al., 2021; Trabucco & De Giovanni, 2021). Resilience can be thought of as an adaptive ability to anticipate unforeseen occurrences, react to them, and recover while maintaining operations (Ponomarov & Holcomb, 2009). It comes about as a result of proactive and reactive skills that are built from collections of routine procedures (Chen et al., 2012).

Researchers have suggested that the structure and complexity of supply networks relate with how much a firm can develop resilience characteristics, which have been defined in past studies as collaboration, flexibility, redundancy, agility, and visibility (Tukamuhabwa et al., 2015). However, the scant research on these subject yields conflicting findings. As argued by Chowdhury et al. (2019), network complexity might have a negative relationship with performance and supply chain resilience, but rather revealed a positive relationship. Also, a study by Wiedmer et al. (2021) shows that an enhanced network complexity can increase flexibility, redundancy, and resilience to disturbance. This suggests that more intricate supply complexity networks might induce several dynamics in the supply chain in relation to both resilience and disruption.

Hence, the two sides of network complexity, which include dark and bright aspects need further assessment. The dark side demonstrates that a complicated network is linked to significant and continuous disturbance. The normal accident theory explains a company's short- and long-term operations and severe disruptions. On the bright side, a complex network allows for greater flexibility and redundancy in supply chains to reduce the risk of disruption with consideration of the theory of diversification.

It must be noted that studies have conceptualized a dark and bright aspect of network complexity with resilience and disruption (Berkes, 2007; Cao et al., 2022; Chowdhury et al., 2019; Wang et al., 2018; Wiedmer et al., 2021). Few or no empirical studies have been conducted on the relationship among network complexity, supply chain disruption and resilience. Also, Prior studies fail to consider various aspects of network complexity and resilience leading to a myopic view of the nexus (see, Chowdhury et al., 2019; Mitra et al., 2017; Wang et al., 2018). This means that some earlier research treated supply chain resilience as a single construct, and omitted the potential that different measures of network complexity might have a unique relationship with each aspect of supply chain resilience and disruption. In the study of Hamidu et al. (2023), the role of disruption was ascertained in the midst of resilience and performance without emphasis on how network complexity can drive resilience or disruption. Also, Chowdhury et al. (2019) explored how network complexity enhances the nexus between resilience and performance. Accordingly, few or no studies have examined how the supply chain network complexity dimension's overall structure can increase disruption risks (dark side), ignoring the fundamental elements of complexity that may arouse asymmetric relationships. It goes to reason that prior studies have not yet investigated how measures of network complexity relate to both resilience strategies and disruption. Therefore, the objective of the current study is to examine the asymmetric relationship of the dimensions of supply chain network complexity to both supply chain resilience and supply chain disruption.

In recognising that handling supply chain disruptions in the contemporary global corporate environment with resilience capabilities demands consideration of many forms of complexity in line with the general systems theory (Bertalanffy, 1968), this study makes a number of contributions to the literature. Supply chain resilience and disruption are utilised to investigate their nexus with network complexity due to their significant contribution to sustainable supply chain management (Kamalahmadi et al., 2022; Tseng et al., 2022). To better understand the relationship with supply chain resilience and disruption, first, we study the various dimensions of network complexity (supply complexity, customer complexity and logistics complexity). Second, three supply chain resilience (SCR) strategies (collaboration, flexibility and redundancy) are employed to investigate the bright side of network complexity. Third, since network complexity may have a favourable or unfavourable bearing due to the existence of several dimensions, this study looks into the dual effect of network complexity addressing its dark and bright side respectively on disruption and resilience strategies.

Findings from the study explicate that supply complexity has a significant positive effect on disruption and the three dimensions of supply chain resilience. However, customer complexity significantly influenced disruption whereas logistic complexity is germane to the three resilience strategies.

The literature review is subsequently presented. This is followed by the study's methodology and results and discussion. The study ends with the conclusion highlighting implications and recommendations.

## 2. Literature review

### 2.1. General systems theory

Bertalanffy (1968) proposed the general systems theory (GST). Organizations, according to traditional organizational theorists, are closed systems that do not include external issues. The external environment has a considerable impact on the organization, as Bertalanffy (1968) discovered. He suggests that, because the supply chain network is a complex system with many internal and external components, the success or failure of an organization or system is determined by the interaction of the system's various internal and external features (Bertalanffy, 1968; Dey, 2016).

The systems theory framework, on which supply chain management is founded, aids in describing the environment in which supply chains function effectively. The GST states that supply chains change over time. Modern information technology has changed how supply chains are managed; thus, they are now different from what they were in the past (Janvier-James, 2012; Melnyk et al., 2022). Additionally, it is anticipated that with time, the nature of the connections between the businesses in the supply chain would improve. Jaradat et al. (2017) contend that in order to comprehend and improve the supply chain, experts must look at it from a system viewpoint.

Systems theory's main objective is to make sure that every part of the system is interconnected and functioning perfectly. To prevent any hiccups and to enhance the flow of people, goods, and services, managers are required to oversee the system (Chowdhury et al., 2019; Hamidu et al., 2023; Luz Tortorella et al., 2022). In order for the system to be full and effective, all the parts of the whole had to be placed together (Stacey, 2011).

When it comes to supply chain network complexity, GST suggests that the complexity of a supply chain network can increase the risk of disruptions. This is because as the supply chain becomes more complex, it becomes harder to identify and manage potential risks and vulnerabilities. The complexity may stem from various factors such as the number of suppliers, customers, logistics, transportation modes, regulations, and technologies (Chowdhury et al., 2019; Hamidu et al., 2023; Yin et al., 2022).

On the other hand, GST also suggests that supply chain resilience can help to mitigate the impact of disruptions (Hamidu et al., 2023). Resilience is the ability of a supply chain to adapt and recover from disruptions quickly (Zighan & Ruel, 2023). A resilient supply chain can anticipate, absorb, and respond to disruptions in a timely and effective manner.

Thus, there is a relationship between supply chain complexity, resilience, and disruption. As supply chain complexity increases, the need for supply chain resilience becomes more critical (Chowdhury et al., 2019). A resilient supply chain can better handle and recover from disruptions, and the ability to recover quickly can reduce the impact of disruptions. Therefore, it is important for supply chain managers to balance the complexity of the supply chain with the level of resilience needed to mitigate the risks of disruptions.

Studying GST would give managers a complete understanding of the business and enable them to effectively coordinate the many parts of the organization to achieve an enhanced SCR (Chowdhury et al., 2019; Holweg & Pil, 2008; Zighan & Ruel, 2023). Systems theory is also dynamic and helps to spot supply chain disruptions; managers would benefit from studying the theory by learning how to deal with problems that impede the system's smooth operation (Hohenstein, 2022; Kopanaki, 2022). This aids in determining if a complex system necessitates more resilience tactics or causes greater disturbance. The current study investigates how supply chain complexity relates to disruption and SCR addressing the dark and bright sides respectively.

## **2.2. Conceptual review**

### **2.2.1. Network complexity**

Enterprises are being stretched to their limitations by a greater variety of products cheaper production costs, and shorter product life cycles, to name a few, which are causing network complexity. Management must comprehend the main complexity drivers and how they interact in order to manage this complexity. Studies advocate that increased network complexity is associated with worse business performance (Christopher & Peck, 2004; Kamalahmadi et al., 2022; Silvestro, 2002; Zhao et al., 2019).

However, network complexity can have a dual impact on resilience following a disruption (Yin et al., 2022). Supply chain complexity can aid in the ability to recover following an interruption; for



instance, a more complex supply base enables businesses to use more suppliers following an interruption, which enhances their capacity to recover. In contrast, a supply chain disruption recovery may be hampered by increased supply complexity. Therefore, this study categorises complexity into supplier-based complexity, customer complexity, and logistical complexity, depending on where the supply network is located instigating their asymmetric effects.

**2.2.1.1. Supply complexity.** When the main business has numerous suppliers who differ in geography, enterprise size, organisational culture, and technical capabilities, the complexity of the supply base rises (Yin et al., 2022). The intricacy of the supply base is increased by the fact that many of these providers have variable and lengthy lead periods.

**2.2.1.2. Customer complexity.** Customer base complexity is a term used to describe downstream complexity, which is frequently related to client counts. In this regard, their level of trust, budgets, emotions, characteristics, among others about markets would be heterogeneous from one customer to another which can influence return rate (Taleizadeh et al., 2023) arousing greater customer complexity. When the primary company's goals meet shifting client demands and expectations, the complexity of the customer base is increased by large customer bases and a variety of finished items with shorter life cycles (Yin et al., 2022).

**2.2.1.3. Logistics complexity.** This is referring to the quantity of carriers in the supply network for the customer or the quantity of arcs in the supply network (Tang, 2006).

## **2.2.2. Supply chain resilience**

Some academics define resilience as a company's ability to adjust to disruptions and restart regular business operations (Blackhurst et al., 2011; Christopher & Peck, 2004). Others view resiliency as a proactive quality displaying an organization's potential to withstand imminent setbacks (Kim et al., 2015). The two, however, have been merged in a recent study, which sees resilience as both a proactive and reactive quality (Melnik et al., 2014; Wieland et al., 2013). Their combination has given resilience a dual outlook (resistance and recovery). Resilience is defined in this perspective as "the capacity to withstand disturbances and recover operational capabilities after disruptions occur." Since it encompasses both the proactive and reactive views of resilience in this study, Tukamuhabwa et al. (2015)'s definition of resilience as "the adaptive capability of a supply chain to prepare for and/or respond to disruptions, to make a timely and cost-effective recovery, and therefore progress to a post disruption state of operations" is adopted. Collaboration, flexibility, and redundancy are just a few of the many skills that businesses may use to improve the perspectives of resilience that have been found by various research (Chowdhury et al., 2019; Hamidu et al., 2023; Zighan & Ruel, 2023). Collaboration, flexibility, and redundancy will be used in this study because they are common in the literature.

**2.2.2.1. Collaboration.** Collaboration, according to Jüttner and Maklan (2011), is defined as two or more elements of the supply chain that are accountable for adopting practices and procedures. Because supply chain management is fundamentally a network theory, risk management must also be considered from a network standpoint (Christopher & Peck, 2004; Kamalahmadi et al., 2022). Collaboration amongst supply chain partners is what binds the network collectively and enables an all-encompassing strategy for supply chain resilience (Scholten et al., 2014). To gain the benefits of collaboration in a supply chain, individual enterprises must align their operations, routines, and procedures in a synchronized manner.

**2.2.2.2. Flexibility.** Flexibility has been defined as "the ability to bend easily without breaking" and has thus been defined as an essential component of resilience (Mandal et al., 2016). Therefore, flexibility refers to a company's ability to modify the design of its supply chain in response to long-term or significant changes in the supply chain and market environment (Shekarian et al., 2020). Flexibility ensures that the supply chain can absorb changes induced by disruptive events through effective and

timely reactions (Mandal et al., 2016). As a result, it is the ability to deal with, handle, and, when necessary, exploit unanticipated emergencies. Flexibility must be included into the supply chain's structure, interorganizational processes, and tactics, according to consensus (Mandal et al., 2016).

**2.2.2.3. Redundancy.** Redundancy is the intentional and deliberate utilisation of inventory and spare capacity that can be relied upon in times of emergency, such as a spike in demand or a supply shortage (Parast & Shekarian, 2019; Shekarian et al., 2020). According to Shekarian et al. (2020), adding redundancy is a good strategy to increase resilience and boost recovery from disturbances. According to Kamalahmadi and Parast (2017), adopting redundancy solutions can increase supply chain resilience in a dynamic and complex business environment that demands reducing the effects of supply chain disruption.

### **2.2.3. Supply disruption**

Supply disruptions are unanticipated events that prevent resources or items from moving normally through a supply chain (Kleindorfer & Saad, 2005; Lusiantoro & Pradipto, 2022). Ivanov et al. (2017) claim that supply disruption, also known as interruptions, can be brought on by a number of factors, including the complexity of the supply market and the importance of the purchased goods. For enterprises, these hazards are viewed as a significant source of operational and financial risks (Kamalahmadi et al., 2022; Kim et al., 2015). Depending on the intensity of the disruption and the buying firm's capacity for recovery, supply disruptions may have a negative impact on the performance of the buying firm in the short and/or long term.

### **2.3. The dark side of network complexity**

The dark side of network complexity relates to the enhancement of supply chain disruption due to a complex network. When the risk of stockouts increases, decision-making becomes more difficult, and financial, market, and industrial performance decline (Wiedmer et al., 2021). Similar to this, more complex products have lower profitability and lower operational and service performance (Silvestro, 2002; Zhao et al., 2019). Additionally, more geographically scattered clients brought on by customer complexity typically result in higher inventory costs (Amjadian & Gharaei, 2022) and longer cash withdrawal cycles for core businesses. This has induced studies, to employ nonlinear models such as an augmented Lagrangian approach (Gharaei, Amjadian, et al., 2023), Generalised Benders Decomposition (GBD) under separability approach (Gharaei, Karimi, et al., 2023), and Lexicographic method (Gharaei et al., 2021) to model large-scale inventory systems. The success of the company may be impacted by a diversified clientele base that exacerbates the effects of demand changes in downstream supply chains.

To monitor and coordinate a supply network with a high number of carriers acting as the network's linkages, more labour is required (Choi & Krause, 2006; Zhao et al., 2019). A company needs to be able to coordinate a network properly. Finding the resilience skills that will allow for effective and efficient collaboration takes time and resources. However, because they are frequently interdependent on one another, managing many interactions between them makes it more difficult to coordinate logistics tasks among multiple carriers (Baloch & Rashid, 2022; Hertz & Alfredsson, 2003). Furthermore, clients with a wide range in demand will negatively impact an enterprise's ability to operate efficiently when the complexity of the customer base is great (Yin et al., 2022). With increasingly diverse clients, transaction costs also rise, decreasing the effectiveness of businesses in managing their customer base.

There seems to be a research gap in terms of the nexus between network complexity and disruption. While Hamidu et al. (2023) focused on the role of disruption, they did not consider the influence of network complexity on disruption. On the other hand, Chowdhury et al. (2019) explored how network complexity can enhance the connection between resilience and performance, but they did not examine the impact of network complexity on disruption. Therefore, a potential research gap would be to investigate the effect of network complexity on disruption.



According to Craighead et al. (2007), a more complicated area of the network will likely be affected by a triggering event, increasing the number of nodes and arcs that are affected and the degree of the disruption. As a result, the amount of time a company needs to plan its response to a disruption may grow, which will in turn make the disruption more severe (Christopher & Peck, 2004; Kamalahmadi et al., 2022).

The following research hypotheses are formulated owing to the above;

**H<sub>1</sub>:** There is a significant relationship between supply network complexity and supply chain disruption.

**H<sub>2</sub>:** There is a significant relationship between customer network complexity and supply chain disruption.

**H<sub>3</sub>:** There is a significant relationship between logistics network complexity and supply chain disruption.

#### **2.4. The bright side of network complexity**

In this study, we define the bright side of network complexity as improvement in resilience strategies following a complex network. If a buyer only purchases a vital section from a deteriorating supplier, a catastrophic disruption may result (Kamalahmadi et al., 2022). In contrast, there is less chance of disruption if a buyer obtains components from a wide variety of providers, maintaining redundant suppliers, which makes the network complex. In the same way that broad stock holdings assist lower risk, Kleindorfer and Saad (2005) propose that disruptions might be reduced by utilising a varied network of suppliers, facilities, and logistics service providers. Similarly, to this, Wiedmer et al. (2021) claims that when supply complexity is larger, that is, when a buying firm purchases from several suppliers, there is less disturbance. Buyers can diversify their supply networks so they have options to use in case a node or arc fails by keeping a portfolio of suppliers and logistics providers (Wiedmer et al., 2021). Buyers might employ diversification in this way to increase the anticipated robustness of their supply networks.

Previous studies have neglected to consider various aspects of network complexity and resilience, resulting in a limited understanding of the relationship between the two (Chowdhury et al., 2019; Mitra et al., 2017; Wang et al., 2018; Zighan & Ruel, 2023). Many earlier studies treated supply chain resilience as a singular construct, failing to recognize that different measures of network complexity may have distinct associations with each aspect of supply chain resilience. As a result, more nuanced and comprehensive analysis is required to better understand the complex interplay between network complexity and supply chain resilience.

We therefore argue that supply complexity, customer complexity and logistics complexity allow a firm to recover from a disruption by relying on the ideas of portfolio diversification theory to promote the positive side of supply network complexity. The following research hypotheses are found based on the above;

**H<sub>4a</sub>:** There is a significant relationship between supply network complexity and supply chain resilience collaboration.

**H<sub>4b</sub>:** There is a significant relationship between supply network complexity and supply chain resilience flexibility.

**H<sub>4c</sub>:** There is a significant relationship between supply network complexity and supply chain resilience redundancy.

**H<sub>5a</sub>:** There is a significant relationship between customer network complexity and supply chain resilience collaboration.

**H<sub>5b</sub>:** There is a significant relationship between customer network complexity and supply chain resilience flexibility.

**H<sub>5c</sub>:** There is a significant relationship between customer network complexity and supply chain resilience redundancy.

**H<sub>6a</sub>:** There is a significant relationship between logistics network complexity and supply chain resilience collaboration.

**H<sub>6b</sub>:** There is a significant relationship between logistics network complexity and supply chain resilience flexibility.

**H<sub>6c</sub>:** There is a significant relationship between logistics network complexity and supply chain resilience redundancy.

### **3. Methodology**

#### **3.1. Research approach and design**

The research approach employed in this study is quantitative in nature, as it aims to provide a numerical assessment of the developed hypotheses. To achieve this, the study adopts an explanatory research design, which allows the researcher to assess the degree of association between the indicators of supply chain network complexities, and supply resilience and disruption. By using this approach, the study seeks to provide a clear understanding of the relationship between the variables under investigation, and solicit data through a survey that can be analysed statistically to draw meaningful conclusions (Saunders et al., 2019).

#### **3.2. Study area**

The study was conducted in Accra Metropolis. As the capital city of Greater Accra region and the most popular city with many firms in manufacturing, the Accra Metropolis forms the major financial, commercial and industrial hub of the country (Akubia & Bruns, 2019; Asare & Angmor, 2015). The Metropolis is also the home to heavy manufacturing industries like textiles, food and beverage, chemical and pharmaceutical, timber and paper manufacturing. This concentration of many manufacturing firms with respect to their activities consequently led to the chosen study area.

#### **3.3. Unit of analysis and sampling**

The targeted population is supply chain managers or managers responsible for the supply chain activities of manufacturing firms in the Accra metropolis of Ghana. The Accra Metropolis holds about 41% of manufacturing firms in Ghana (Ghana Statistical Service [GSS], 2015). These manufacturing companies span the nation's local and multinational manufacturers. The reason for choosing these two categories of manufacturing companies is that multinational corporations are thought to be more vulnerable to different degrees of SCD and have a more sophisticated network than local corporations (Coe et al., 2017). Consequently, research into the two categories produced intriguing data for the concept.

Ghana's most significant manufacturing sectors include the smelting of aluminium, food and beverage production, oil refining, cement production, clothing and textile production, chemical and pharmaceutical production, and the processing of metals and wood products. Over 250,000 people are reportedly employed in this industry, which also contributes about 9% of the GDP (Quarshie et al., 2017).

Manufacturing firms in general would be considered because they have high potency of facing supply chain disruption which requires that effective and efficient innovation and resilience strategies are instituted as averred by Dey (2016). This is supported by Singh et al. (2019) and Han et al. (2020) who revealed that out of all the sectors, manufacturing firms faced the highest supply chain disruption. Supply chain managers, procurement officers, logistics and warehouse managers were used because they are directly responsible for the activities of the supply chain. They oversee and manage every stage of production flow from upstream through to the downstream and as such can provide accurate supply chain information. The population size for this study included 2495 manufacturing firms in the Accra metropolis (GSS, 2015).

However, since it is impracticable to use the entire population size it is relevant to sample. Also, considering the fact that manufacturing firms in Accra Metropolis are homogeneous in terms of supply disruption, network complexity (Han et al., 2020; Singh et al., 2019), and form part of a single sector with similar business activity of manufacturing goods, a sample from the population would provide better inferences. In this manner, the sample size was estimated based on the formula provided by Yamane (1967) with a margin of error of 5% and a 95% confidence level. The formula according to Yamane can be expressed as

$$n = \frac{N}{1 + Ne^2}$$

where  $n$  depicts sample size,  $N$  shows population size and  $e$  signifies margin of error.

The study therefore determines the required sample size to be

$$n = \frac{2495}{1 + 2495 \times 0.05^2}$$

$$n = 344.73$$

As a result, the minimum sample size for the study from a population of 2495 was approximately 345 manufacturing firms in Accra Metropolis. The final sample size utilised for the study was 690 which is above the minimum sample size of 345 for this survey study. The sampling procedure was simple random. This is because the manufacturing firms were considered to be homogeneous, and as such categorisations of these manufacturing firms do not matter in the current studies' context. The manufacturing sector in Ghana has been confirmed to exhibit common characteristics of supply chain disruptions and network complexity requiring resilient strategies (Han et al., 2020; Singh et al., 2019). Moreover, manufacturing firms represent a single sector exhibiting homogeneous groupings (Castelo-Branco et al., 2019). As such, as other probability sampling techniques would have been beneficial to the current study, we do not compare or test differences between and among groups of manufacturing firms as a core direction of our research objective, hence, assuming a homogeneous sample in this case, is the best. With the help of the simple random sampling approach, the manufacturing firms were chosen classified by location codes through the random number generation in excel statistical software. Furthermore, the respondents included in the study were managers in charge of any of these roles—supply chain, operations and logistics. Consequently, the most immediate and available manager at the point of data collection was consulted to provide response to the questionnaire items from each of the selected firms.

### 3.4. Data collection instruments and procedures

The researcher employed primary data for this study. The study designed and administered questionnaire to collect primary data from supply chain managers of manufacturing firms in the form of a survey. The use of questionnaire ensures utmost uniformity and objectivity (Hamawandy et al., 2021). The questionnaires were structured to facilitate quicker and economical means of obtaining data from a sufficiently vast population, and ensuring that they understand the questionnaire. The questionnaire also guarantees anonymity of respondents and thus

they feel confident to provide the relevant information needed for the work (Hamawandy et al., 2021).

The study adopted a seven-point Likert scale to measure various constructs from 1- Strongly disagree to 7- Strongly agree. A 7-point Likert scale is more reliable, simpler to use, and a better representation of the real assessment of a response (Taherdoost, 2019). Given all of these benefits, 7-point items seem to be the ideal option for questionnaires like those used in usability studies, even when compared to higher-order items (Chyung et al., 2018). The questionnaire in support of the study was adopted from various sources which ensured convergent validity, and corresponds to the study's setting. Table 1 presents the sections of the questionnaire, how they are measured in this study, number of items for each construct as well as those who developed them. Issues relating to construct validity and reliability are subsequently provided.

A thorough analysis of the research on the variables used in the study led to the creation of questionnaires that gathered information from industrial firms. To reduce worries about common method bias, the questionnaires were constructed in accordance with the standards outlined by Podsakoff et al. (2003). In particular, the questionnaire was compiled from a variety of sources and included sections with measurable items that were clearly separated from one another. The researcher also supported the use of reverse questioning for the majority of survey items. To prevent collinearity and ultimately reduce common method bias, the inner variance inflation factor (VIF) for each construct's elements was evaluated.

The primary data used in support of this study was collected using the survey method. To gather information from manufacturing companies in Accra Metropolis, the study used a structured questionnaire created in accordance with the study's objectives. The process involved the distribution of a structured questionnaire to respondents followed by a collection of the filled questionnaire. In particular, the researcher and three professionally trained assistants handed out the surveys to the respondents.

The consent of respondents was sought before the needed data were gathered (Sarantakos, 2005). This is due to the fact that when participants willingly accept to participation in a study, it is assumed that they are aware of both the study's potential advantages and its potential risks. In order not to put pressure on the respondents, an ample time was given to them to answer the

**Table 1. Measurement of variables and sources**

Variable	Measurement	Items	Source
<b>Section A:</b> Demographics		8	Baafi et al. (2020)
<b>Section B:</b> Supply chain resilience	Endogenous	14	Chowdhury and Quaddus (2016), Mandal et al. (2016), and Zouari et al. (2020)
SCRC		5	
SCRF		4	
SCRR		5	
<b>Section D:</b> Supply disruption	Endogenous	10	Wong et al. (2020) and Zsidisin and Wagner (2010)
<b>Section E:</b> Network complexity	Exogenous	13	Chowdhury et al. (2019)
SNC		4	
CNC		5	
LNC		4	

questionnaire for subsequent collection. Most of the respondents appropriately responded to the agreed time and facilitated the successful collection of the data.

The manufacturing companies in Accra Metropolis received a total of 800 questionnaires. This was done to make sure the representativeness requirement of a minimum sample size of 345 manufacturing companies was met. To reach a total response rate of 86.25%, 690 out of the 800 questionnaires that were sent were returned. The final sample size of 690 is considered appropriate for this study because it statistically exceeds the minimum sample size under Yamane's (1967) approach.

### 3.5. Pre-testing and reliability

A preliminary investigation of the survey was performed to ensure that the instructions, questions and scale item errors are minimised (Pallant, 2016). It further provides the opportunity to understand the questions appropriate to facilitate the required responses. This exercise was performed after the questionnaire was approved by my supervisors. A sample size of ten (10) was selected for the pre-testing which is in line with the assertion of Saunders et al. (2019) on the benchmark for pilot studies by students. The outcome from the pre-testing depicted those scales were clear to the respondents and considered appropriate for further analysis.

The reliability of the study's constructs was examined to ensure consistency and minimise biases in the study. To accomplish this purpose, the Cronbach's Alpha coefficient as shown in Table 2 was estimated on the pre-test data.

The study follows the assertion made by Pallant (2016) on the desirable Cronbach's Alpha of at least 0.7 depicting internal consistency of the constructs of the main research variables. A look at the Cronbach's Alpha coefficients in Table 2 shows that the study's constructs have good internal consistency.

### 3.6. Ethical consideration

Fraenkel and Wallen (2000) asserted that it is important to keep confidential information collected from respondents. Respondents were satisfactorily informed prior to obtaining their consent. The researcher's goals and intent were made known to the respondents. As a consequence, an introductory letter which explains the study's goals and guaranteed confidentiality were obtained. This letter was meant to introduce the researcher to the firms to seek their necessary assistance. In addition, the ethical clearance letter indicating the researcher had ethically cleared and deemed fit to proceed with data collection was obtained and a copy was given to firms who requested them. The study offered a guarantee of anonymity and confidentiality to participants by ensuring that respondents' names are not identified with the questions.

**Table 2. Construct reliability**

Constructs	No. of items	Cronbach's Alpha
SCRC	5	0.898
SCRF	4	0.799
SCRR	5	0.821
SNC	4	0.889
CNC	5	0.790
LNC	4	0.881
Supply disruption	10	0.879

### 3.7. Data processing and analysis

The data received from the supply chain managers were entered in excel software and cleaned for further statistical analysis. To minimise errors in data entry, codes were assigned to each questionnaire and matched with the required entry on the excel software. The researcher employed inferential statistics, thus the Partial Least Square Structural Equation Modelling (PLS-SEM). The PLS-SEM estimation technique from the Smart PLS version 4 statistical software was used to accomplish the research objectives. The choice of the PLS-SEM statistical tool was based on its efficacy in effectively examining relationships between latent variables (Hair et al., 2012).

In this study, the PLS-SEM approach was used to analyse the data. This is due to the fact that PLS-SEM does not impose data normality restrictions and also gives reliable results even with a small sample size, in contrast to covariance-based SEM (CB-SEM).

## 4. Results and discussion

### 4.1. Preliminary statistics

The profile of responders is shown in Table 3 using frequency and percentages (%). In order to provide a basic overview of the respondents, a total of six demographic characteristics were recorded. Seven demographic traits are displayed with their corresponding category, frequency, and percentages.

It can be seen from Table 3 that males dominate the study sample accounting for about 64.1%. Respondents with undergraduate qualification are the majority, followed by graduate qualification. Respondents whose position is operations constitute 40.3% of the sample size. The next is logistics managers with a percentage of 26.4%. Since supply chain activities in Ghana is still evolving, supply chain managers were the least represented in the sample. Moreover, individuals with working experience between 6–10 years constitute the majority, followed by between 11–15 years, then 1–5 years. Few managers have longer experience with manufacturing firms. Again, samples are drawn from managers who assume positions such as Supply chain managers (19.1%), Operations managers (40.3%), Logistics managers (26.4%) and others (14.2%). The study's sample is made up of individuals from diverse manufacturing sectors with food and beverage dominating (about 31.9%) whereas others recorded the least (2.3%). There are also varying levels of business forms to enhance the diversity of the sample.

The study also shows the preliminary statistics of the research variables. The variables are supply complexity (SNC), customer complexity (CNC), and logistics complexity (LNC), supply chain resilience collaboration (SCRC), supply chain resilience flexibility (SCRF) and supply chain resilience redundancy (SCRR), and supply chain disruption (SCD). The descriptive statistics under consideration in this study are shown in Table 4.

As shown in Table 4, the average values for supply chain disruptions, variants of supply chain network complexity and supply chain resilience above 4, implying moderate to high levels. There is also consistency in responses except for firm age as indicated by the standard deviation. Hence, it can be noticed that the age of business is the least consistent. Additionally, the majority of the factors are negatively skewed, suggesting that lower scoring values may be possible than higher ones. As a result, the majority of the variables are not symmetric. The leptokurtic distribution of the data is suggested by the greater kurtosis values above 1.5. The Jarque-Bera statistic (p-value 0.01) indicates that the data are not normally distributed since most variables have deviations from both symmetry and mesokurtic distribution. For this investigation, the assumption of nonnormality allows the use of a parametric test. Therefore, this study specifically uses the PLS-SEM technique.



**Table 3. Demographic characteristics of respondents**

Category	Category	Frequency	Percentage (%)
Gender	Male	442	64.1
	Female	248	35.9
Educational qualification	Undergraduate	376	54.5
	Graduate	302	43.8
	Post-Graduate	12	1.7
Years of work experience	1–5 Years	146	21.2
	6–10 Years	366	53
	11–15 Years	156	22.6
	Above 16 Years	22	3.2
Form of Business	Sole proprietorship	288	41.7
	Limited liability company	170	24.6
	Partnership	224	32.5
	Other	8	1.2
Position in the organization	Supply chain manager	132	19.1
	Operations manager	278	40.3
	Logistics manager	182	26.4
	Other	98	14.2
Manufacturing sector	Clothing and textiles	182	26.4
	Food and beverage	220	31.9
	Oil and gas exploration and production	80	11.6
	Chemical and pharmaceutical	70	10.1
	Pulp and paper	4	0.6
	Agricultural production	82	11.9
	Electronics	36	5.2
	Other	16	2.3

**Table 4. Descriptive statistics of constructs**

	Mean	Std. Dev.	Skewness	Kurtosis	Jarque-Bera
CNC	5.514	1.006	−1.794	6.642	375.643***
LNC	4.588	0.830	−0.375	2.739	9.085***
SCD	5.830	0.919	−2.044	8.597	690.460***
SCRC	5.872	1.138	−2.235	8.102	661.519***
SCRF	5.826	1.166	−2.090	7.430	533.194***
SCRR	5.958	1.153	−2.281	8.085	670.735***
SNC	5.988	1.107	−2.357	8.760	796.505***
AGE	7.354	4.128	0.732	4.130	49.123***

Notes: SNC, CNC, and LNC denote supply complexity, customer complexity, and logistics complexity respectively. SCRC, SCRF and SCRR stand for supply chain resilience collaboration, supply chain resilience flexibility and supply chain resilience redundancy. SCD means supply chain disruption. \*\*\* denotes significance at 1%.

## 4.2. Measurement model assessment

### 4.2.1. Construct reliability, indicator reliability, and convergent validity

We investigate the measurement model assessment through construct reliability (as measured by Cronbach's Alpha and rho\_A), the indicator's reliability (loadings), convergent validity, and discriminant validity (Hair et al., 2016). Construction dependability was also assessed using composite reliability (CR). Cronbach's alpha (CA) and rho\_A were used to evaluate construct reliability from Table 3, which displays the percentage of an indicator's variance that can be explained by its underlying latent variable (Hair et al., 2012). The cut-off is that rho\_A scores and CA should be at least 0.70 to ensure satisfactory and acceptable results. Table 5 also displays the study's convergent validity based on the Average Variance Extracted (AVE) score (Hair et al., 2012). The AVE describes how the concept captures the variation of an indicator in relation to the total variance and the variance due to measurement error (Hair et al., 2012). As recommended by Bagozzi and Yi (1988), the general rule is that all AVE scores must be at least 0.50 for each build.

A glance at Table 5 indicates that all the indicators loaded well with at least 0.7 loading coefficient which is considered acceptable (Hair et al., 2016). The Cronbach's alpha (CA) and rho\_A loadings at Table 3 confirm the indicator's rule of thumb of 0.7. The composite reliability (CR) presented in Table 3 explains the extent to which combined indicators of distinct constructs are sufficiently measuring those constructs (Ringle et al., 2012). The general rule is that CR scores must be  $\geq 0.70$  (Bagozzi & Yi, 1988). Table 5 shows that the constructs have composite reliability (CR) values above 0.7 in all cases, indicating that the constructs are resilient (Straub, 1989).

Additionally, all indicators with AVE values greater than 0.6 are loaded to exhibit convergent validity (Hair et al., 2014). From Table 5, the least AVE is 0.675 which is in line with the recommendation by Fornell and Larcker (1981), indicating that the products have higher volatility on average than the variance described by the concept. Because all hidden variables have an AVE beyond 0.5, the results show the model's convergent validity.

### 4.2.2. Discriminant validity

Table 6 presents the model's quality by evaluating the constructs' discriminant validity (Hair et al., 2012). According to Hair et al. (2014), the discriminant validity evaluates the structural model for collinearity problems. The discriminant validity is tested using the Heterotrait-monotrait ratio (HTMT).

The HTMT performs better since it can identify a lack of discriminant validity in typical study circumstances. As a general rule, HTMT values (correlation values among the latent variables) should be less than 1.0 in order to obtain discriminant validity. All of the construct values in Table 6 were less than 1.0. This shows that each construct is separate from the others in a very apparent way.

We further show the predictive power of the indicators using the  $Q^2$  predict approach as presented in Table 5. Prior to determining the indicators' predictive value or power, the PLS-SEM results are contrasted with those of the linear model (LM). The predictive ability of the numerous potential indicators and constructs that served as endogenous variables in the SEM is shown in Table 7. The  $Q^2$ predict is first reviewed to make sure that the predictions outperform the naivest (above 0) benchmark (Hair et al., 2020; Pesämaa et al., 2021). If the predicted outcomes are better than the baseline value, then other prediction statistics, such as RMSE and MAE, can be explored (above 0).

According to Hair et al. (2020), the RMSE values are compared to a baseline value created by a linear regression model (LM) that generates predictions for the measured variables in order to evaluate the prediction error of a PLS-SEM analysis (indicators). Four (4) rules were presented, and they had to be followed. The first rule states that the model lacks predictive power when the RMSE or MAE have higher prediction errors for all endogenous variable indicators compared to the naïve

**Table 5. Summary of measurement scale**

<b>LV</b>	<b>Loadings</b>	<b>CA</b>	<b>Rho_A</b>	<b>CR</b>	<b>AVE</b>
<b>CNC</b>		0.937	0.939	0.955	0.842
CNC1	0.877				
CNC2	0.931				
CNC3	0.927				
CNC5	0.933				
<b>LNC</b>		0.905	0.911	0.955	0.913
LNC1	0.952				
LNC4	0.960				
<b>SCD</b>		0.939	0.941	0.949	0.675
SCD2	0.749				
SCD3	0.857				
SCD4	0.755				
SCD5	0.836				
SCD6	0.806				
SCD7	0.839				
SCD8	0.867				
SCD9	0.856				
SCD10	0.818				
<b>SCRC</b>		0.950	0.951	0.962	0.834
SCRC1	0.911				
SCRC2	0.907				
SCRC3	0.913				
SCRC4	0.932				
SCRC5	0.903				
<b>SCRF</b>		0.923	0.924	0.945	0.812
SCRF1	0.883				
SCRF2	0.898				
SCRF3	0.912				
SCRF4	0.911				
<b>SCRR</b>		0.954	0.955	0.965	0.845
SCRR1	0.921				
SCRR2	0.922				
SCRR3	0.932				
SCRR4	0.942				
SCRR5	0.877				
<b>SNC</b>		0.923	0.924	0.945	0.813
SNC1	0.860				
SNC2	0.913				
SNC3	0.926				
SNC4	0.906				

Notes: SNC, CNC, and LNC denote supply complexity, customer complexity, and logistics complexity respectively. SCRC, SCRF and SCRR stand for supply chain resilience collaboration, supply chain resilience flexibility and supply chain resilience redundancy. SCD means supply chain disruption.

**Table 6. HTMT**

	<b>CNC</b>	<b>LNC</b>	<b>SCD</b>	<b>SCRC</b>	<b>SCRF</b>	<b>SCRR</b>	<b>SNC</b>
CNC	0.000						
LNC	0.836						
SCD	0.717	0.614					
SCRC	0.574	0.533	0.564				
SCRF	0.597	0.579	0.532	0.916			
SCRR	0.616	0.566	0.561	0.978	0.919		
SNC	0.984	0.817	0.717	0.607	0.632	0.634	0.000

Notes: SNC, CNC, and LNC denote supply complexity, customer complexity, and logistics complexity respectively. SCRC, SCRF and SCRR stand for supply chain resilience collaboration, supply chain resilience flexibility and supply chain resilience redundancy. SCD means supply chain disruption.

**Table 7. Predictive power**

<b>Q<sup>2</sup> predict</b>	<b>PLS-SEM_RMSE</b>	<b>PLS-SEM_MAE</b>	<b>LM_RMSE</b>	<b>LM_MAE</b>
SCD10	<b>0.299</b>	<b>1.009</b>	0.739	1.029
SCD2	<b>0.224</b>	<b>0.920</b>	0.611	0.923
SCD3	<b>0.359</b>	<b>0.939</b>	0.725	0.951
SCD4	<b>0.262</b>	<b>0.999</b>	0.717	1.009
SCD5	<b>0.355</b>	<b>0.899</b>	0.655	0.892
SCD6	<b>0.278</b>	<b>0.950</b>	0.691	0.950
SCD7	<b>0.314</b>	<b>0.961</b>	0.696	0.965
SCD8	<b>0.332</b>	<b>0.920</b>	0.669	0.920
SCD9	<b>0.296</b>	<b>0.982</b>	0.732	0.990
SCRC1	<b>0.264</b>	<b>0.988</b>	0.610	1.002
SCRC2	<b>0.237</b>	<b>1.145</b>	0.813	1.152
SCRC3	<b>0.281</b>	<b>1.108</b>	0.758	1.111
SCRC4	<b>0.244</b>	<b>1.112</b>	0.769	1.113
SCRC5	<b>0.269</b>	<b>1.012</b>	0.718	1.009
SCRF1	<b>0.248</b>	<b>1.029</b>	0.635	1.056
SCRF2	<b>0.304</b>	<b>1.104</b>	0.774	1.122
SCRF3	<b>0.285</b>	<b>1.083</b>	0.738	1.091
SCRF4	<b>0.251</b>	<b>1.202</b>	0.802	1.197
SCRR1	<b>0.322</b>	<b>0.998</b>	0.685	0.999
SCRR2	<b>0.250</b>	<b>1.091</b>	0.730	1.098
SCRR3	<b>0.307</b>	<b>1.018</b>	0.708	1.033
SCRR4	<b>0.312</b>	<b>1.033</b>	0.714	1.043
SCRR5	<b>0.272</b>	<b>1.147</b>	0.798	1.171

Notes: SCRC, SCRF and SCRR stand for supply chain resilience collaboration, supply chain resilience flexibility and supply chain resilience redundancy. SCD means supply chain disruption.

LM benchmark, and the second rule states that when majority of the endogenous variable indicators have higher prediction errors in comparison to the naive LM benchmark, the model has low predictive power. Third, when an equal or minority of the endogenous construct indicators have higher prediction errors compared to the naive LM benchmark, the model has medium predictive power. Fourth, when none of the endogenous construct indicators exhibit RMSE or MAE prediction errors that are more than the naive LM benchmark, the model is said to have a strong power for prediction.

Table 7 shows that the Q2 predict values surpass the most naive LM benchmark. From Table 7, it can be seen that the model has a strong power for prediction because none of the endogenous construct indicators had bigger prediction errors compared to the naive LM benchmark, except for some few values for MAE. These values are PLS-SEM RMSE and MAE values, which are shown in bold. In this situation, it can be assumed that the PLS-SEM model has greater predictive power.

#### 4.3. Structural model assessment

After achieving constructs and indicator reliability, as well as convergent and discriminant validity, the study goes ahead to examine the research hypotheses. This work was completed by analysing the direction and strength using the coefficients, p-values reflecting the degree of significance using 5000 bootstraps, coefficient of determination (Adjusted R<sup>2</sup> and R Square), Q<sup>2</sup> predict, root mean squared error, mean absolute error, effect size (f<sup>2</sup>) and variance inflation factor (VIF) in Table 8. The confidence interval (CI) showing both upper and lower bounds for each path relationship is recorded in this study to confirm the significance of the research hypotheses. The decisions in the case of the research hypotheses are further provided in Table 8.

From Table 8, there are two categories of endogenous variables (SCD and SCR) considered in this study. The SCR strategies are subdivided into SCRC, SCRF and SCRR. It can be observed from Table 8 that the maximum VIF of 3.754 which is lower than 5 (Hair et al., 2014) reveals that the pathways are free of multicollinearity. The effect size measure (f<sup>2</sup> < 0.3) presented in Table 8 shows that network complexity has a small effect (on SCRC, SCRF, SCRR and SCD. The model provided by the effect of all factors of supply chain network complexity on from Table 8 denotes that network complexity factors explain 46.9%, 33.1%, 35.6% and 36.9% of the variations in SCRC, SCRF, SCRR and SCD respectively as indicated by the Adjusted R Square. Also, the closeness of the Q<sup>2</sup> predict to R Square and Adjusted R Square suggests that there is indeed a prediction ability for the constructs as found for the indicators of the dependent variables of a greater predictive power.

As noticeable from Table 8, the supported hypotheses included; H<sub>1</sub>: There is a significant relationship between supply network complexity and supply chain disruption; H<sub>2</sub>: There is a significant relationship between customer network complexity and supply chain disruption; H<sub>4a</sub>: There is a significant relationship between supply network complexity and supply chain resilience collaboration; H<sub>4b</sub>: There is a significant relationship between supply network complexity and supply chain resilience flexibility; H<sub>4c</sub>: There is a significant relationship between supply network complexity and supply chain resilience redundancy; H<sub>6a</sub>: There is a significant relationship between logistics network complexity and supply chain resilience collaboration; H<sub>6b</sub>: There is a significant relationship between logistics network complexity and supply chain resilience flexibility; and H<sub>6c</sub>: There is a significant relationship between logistics network complexity and supply chain resilience redundancy.

Conversely, research hypotheses that were not supported included; H<sub>3</sub>: There is a significant relationship between logistics network complexity and supply chain disruption; H<sub>5a</sub>: There is a significant relationship between customer network complexity and supply chain resilience collaboration; H<sub>5b</sub>: There is a significant relationship between customer network complexity and supply chain resilience flexibility; and H<sub>5c</sub>: There is a significant relationship between customer network complexity and supply chain resilience redundancy.

The summary fit outcome in Table 9 has the model's Standardised Root Mean Square Residual (SRMR) which ought to be less than 0.08 (see, Henseler et al., 2016; Hu & Bentler, 1999) while the closer the Normed fit index (NFI) value to 1.00 the better the fit.

It can be noticed from Table 9 that the model's SRMR values of 0.040 and 0.043 are lower than 0.08 indicating a good model fit of minimal discrepancies between observed and expected correlations. Furthermore, the NFI value is higher than the cut-off 0.8, hence, the model is deemed to have marginal fit.

Table 8. Summary statistics										
Variables	Beta (O)	SD(6)	TS(O/6)	P values	f <sup>2</sup>	VIF	CI			Decision
							Upper	Lower		
H <sub>1</sub> : SNC →SCD	0.300	0.101	2.966	0.003	0.027	3.228	0.092	0.489		Supported
H <sub>2</sub> : CNC → SCD	0.329	0.105	3.124	0.002	0.030	3.754	0.127	0.541		Supported
H <sub>3</sub> : LNC →SCD	0.091	0.056	1.630	0.103	0.006	2.534	-0.014	0.211		Not Supported
H <sub>4a</sub> : SNC →SCRC	0.407	0.150	2.715	0.007	0.040	3.228	0.116	0.707		Supported
H <sub>4b</sub> : SNC →SCRF	0.406	0.135	3.002	0.003	0.041	3.228	0.140	0.683		Supported
H <sub>4c</sub> : SNC →SCRR	0.342	0.155	2.212	0.027	0.030	3.228	0.042	0.658		Supported
H <sub>5a</sub> : CNC →SCRC	0.057	0.150	0.382	0.703	0.001	3.754	-0.245	0.339		Not Supported
H <sub>5b</sub> : CNC →SCRF	0.028	0.139	0.200	0.842	0.000	3.754	-0.255	0.289		Not Supported
H <sub>5c</sub> : CNC →SCRR	0.153	0.157	0.974	0.330	0.006	3.754	-0.167	0.447		Not Supported
H <sub>6a</sub> : LNC →SCRC	0.148	0.071	2.095	0.036	0.013	2.534	0.017	0.296		Supported
H <sub>6b</sub> : LNC →SCRF	0.205	0.082	2.501	0.012	0.026	2.534	0.053	0.382		Supported
H <sub>6c</sub> : LNC →SCRR	0.153	0.071	2.152	0.031	0.015	2.534	0.021	0.302		Supported
Exogenous Variables		R Square	Adjusted R2	Q <sup>2</sup> predict		RMSE	MAE			
SCD		0.474	0.469	0.456		0.748	0.541			
SCRC		0.337	0.331	0.313		0.843	0.516			
SCRF		0.362	0.356	0.339		0.826	0.524			
SCRR		0.375	0.369	0.350		0.819	0.512			

Notes: → shows effect from one variable (exogenous variable) to another (endogenous). SNC, CNC, and LNC denote supply complexity, customer complexity, and logistics complexity respectively. SCRC, SCRF and SCRR stand for supply chain resilience collaboration, supply chain resilience flexibility and supply chain resilience redundancy. SCD means supply chain disruption. Beta, SD, TS, CI, RMSE and MAE denote path coefficients, standard deviation, test statistics, confidence interval, root mean squared error and mean absolute error respectively.



**Table 9. Fit summary**

	Saturated model	Estimated model
SRMR	0.036	0.160
d_ULS	0.716	14.395
d_G	0.821	1.665
Chi-square	1020.169	1100.876
NFI	0.880	0.814

The study further presents the PLS structural equation modelling path coefficients and significance in Figure 1 after accomplishing the diagnostics tests. Figure 1 gives the opportunity to address the research hypotheses in a single model. The factor loadings are excluded to enhance clarity for easy interpretation.

From Figure 1, SNC has a significant positive relationship with SCRC ( $\beta = 0.407$ ,  $p$ -value  $< 0.05$ ), SCRR ( $\beta = 0.342$ ,  $p$ -value  $< 0.05$ ), SCRF ( $\beta = 0.406$ ,  $p$ -value  $< 0.05$ ), and SCD ( $\beta = 0.300$ ,  $p$ -value  $< 0.05$ ) of manufacturing firms. Manufacturing companies with various suppliers who vary in region, corporate size, organizational culture, and technical capabilities can be used as examples of how SNC may promote both resilience and disruption. The fact that many of these suppliers have erratic and protracted lead times add to the complexity of the supply base to have dynamic nexus as bright and dark side. This highlights that SNC has both a bright and dark side with respect to supply chain resilience and disruption respectively.

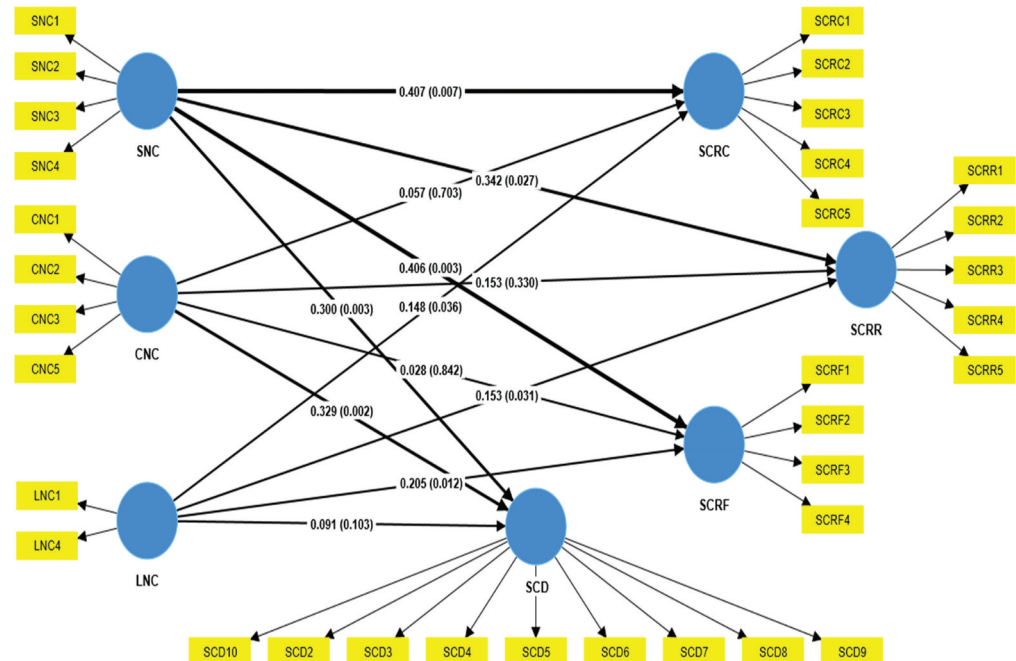
On the other hand, CNC has a significant positive effect only on SCD ( $\beta = 0.329$ ,  $p$ -value  $< 0.05$ ) whereas LNC has a significant positive effect on all the resilience strategies; SCRC ( $\beta = 0.148$ ,  $p$ -value  $< 0.05$ ), SCRR ( $\beta = 0.153$ ,  $p$ -value  $< 0.05$ ) and SCRF ( $\beta = 0.205$ ,  $p$ -value  $< 0.05$ ). It goes to reason that CNC and LNC are respectively particular to the dark and bright side.

The positive effect of SNC and LNC on SCR agrees with the outcome of Iftikhar et al. (2022) conducted on 166 Pakistani firms. Borrowing from the portfolio theory of diversification, complex networks (SNC and LNC) allow companies to spread their risks for greater flexibility, collaboration and redundancy in supply chains. For instance, a complex supply base enables businesses to use more suppliers following an interruption, which enhances their capacity to recover. To reduce the risk of disruptions, it is beneficial for buyers to source components from a diverse range of providers and maintain redundant suppliers, even though this can make the network more complex. This strategy, similar to broad stock holdings, has been proposed by Kleindorfer and Saad (2005) as a means of mitigating disruptions by utilizing a varied network of suppliers, facilities, and logistics service providers. Recent research by Wiedmer et al. (2021) further supports this idea, suggesting that a higher degree of supply complexity, achieved through purchasing from multiple suppliers, can reduce the likelihood of disruptions. By diversifying their supply networks and keeping a portfolio of suppliers and logistics providers, buyers can ensure they have options in case of a node or arc failure, ultimately increasing the anticipated robustness of their supply networks. Employing such diversification strategies can thus be an effective way for buyers to manage supply chain risks.

Conversely, the dark side demonstrates that complex networks—SNC and CNC—are linked to significant and continuous disturbance. For CNC, customers with a wide range in demand contribute negatively to manufacturing companies' ability to operate efficiently when the complexity of the customer base is substantial (Yin et al., 2022). This is not surprising because with increasingly diverse customers, transaction costs upsurge, thereby dwindling the effectiveness of manufacturing firms in managing their customer base. A triggering event is more likely to have an impact on a more complex part of the network, increasing the number of nodes and arcs that are impacted as well as the severity of the disruption (Craighead et al., 2007). Because of this, the

**Figure 1. Effect of supply chain network complexity dimensions on supply chain resilience strategies and disruption.**

Note: SNC, CNC, and LNC denote supply complexity, customer complexity, and logistics complexity respectively. SCRC, SCRF and SCRR stand for supply chain resilience collaboration, supply chain resilience flexibility and supply chain resilience redundancy. SCD means supply chain disruption. P-values are shown in brackets whereas coefficients are presented outside brackets.



amount of time required for a corporation to prepare its reaction to disruption may increase, which will make the interruption more severe (Christopher & Peck, 2004; Kamalahmadi et al., 2022). The normal accident theory is revealed in this study, providing that higher system complexity results in more frequent and severe disruptions. It must also be noted that SNC has an impact on disruption, and this can occur, for instance, if a buyer only purchases a vital section from a deteriorating supplier (Kamalahmadi et al., 2022).

As indicated, supply chain network complexity dimensions have proven to have asymmetric relationship with SCR and disruption supported by the General Systems theory and the accident theory. In this manner, the success or failure of a network complexity depends on how it channels through resilience and disruption of the supply chain.

The insignificant coefficients included relationships between logistics network complexity and disruption, as well as customer network complexity and all the resilience strategies employed in this study. It must be noted that the nature of logistics complexity among the manufacturing firms in Ghana is less connected to disruption. This is because manufacturing firms in Ghana coordinate the multiparty entities in the supply chain to efficiently manage the complex supply network and the firm's cumbersome process in procuring materials have a stronger affinity for supply chain resilience strategies rather than inciting disruption. Furthermore, having multiple buyers for each product, customers coming from a variety of places throughout the world, firms having a variety of finished goods with a shorter life cycle and the wider variety of requirements of customers are not necessary for supply chain resilience strategies.

## 5. Discussion

### 5.1. Summary of findings

Since earlier studies fail to consider various aspects of network complexity and resilience (see, Chowdhury et al., 2019; Mitra et al., 2017; Wang et al., 2018), the following new key findings were revealed as a unique contribution to the scant literature. The first research hypothesis on the relationship between supply complexity and disruption was supported by a positive and significant path coefficient. The second hypothesis on the nexus between customer complexity and disruption

was also supported by a positive and significant path coefficient. On the other hand, the third research hypothesis on logistics complexity and disruption was revealed to be insignificant. Nine hypotheses were found in connection between the three supply chain network complexity and the three resilience strategies. The fourth research hypothesis with three sub-hypotheses were supported to have a significant positive relationship between supply complexity and resilience (SCRC, SCRF and SCRR). Also, from the fifth research hypothesis with three sub-hypotheses, customer complexity was found not to have significant relationship with resilience, and thus not supported. Furthermore, we found reasonable evidence from the sixth research hypothesis to support that logistics complexity has a significant positive relationship with supply chain resilience strategies (SCRC, SCRF and SCRR).

Wiedmer et al. (2021) suggests that having a portfolio of suppliers with the required risk minimisation strategy is ideal to mitigate the impact of disruptions when they occur. However, the study finds that by diversifying supplier and logistics portfolios, firms can improve their capacity to deal with disruption. Markedly, it is not always the case that a complex network would induce supply chain disruptions in line with the outcomes by Wiedmer et al. (2021) and Yin et al. (2022). This contradicts the assertions made by prior studies that a complex network drives disruptions in the supply chain (see, Christopher & Peck, 2004; Dey, 2016; Kamalahmadi et al., 2022; Silvestro, 2002; Zhao et al., 2019). It can therefore be concluded that network complexity has an asymmetric relationship with disruption and resilience strategies addressing the dark and bright side of network complexity.

## 5.2. Theoretical contribution

The significant positive relationship between network complexity and supply chain disruption is supported by the normal accident theory (NAT). According to NAT, complex systems, such as supply chains, are characterized by multiple interdependent components that interact in unpredictable ways. When one component fails, it can trigger a chain reaction of failures throughout the system, leading to an accident. The NAT is revealed in this study, providing that higher system complexity corresponds to more frequent and severe disruptions. This explicates that accidents are inherent in complex systems and become more likely as the number of interdependent components increases.

On the positive relationship between network complexity and supply chain resilience, the portfolio diversification theory provides a strong rationale. By diversifying their supplier and logistics portfolios, firms can extenuate the risks of disruptions in their supply chains. For instance, if a node fails, companies can rely on other suppliers or logistics providers to ensure that their operations continue without any significant interruptions. This approach is particularly relevant for manufacturing firms that require a constant supply of raw materials and other inputs. By diversifying their supply networks, these firms can increase the robustness of their operations and reduce the likelihood of supply chain disruptions that could negatively affect their production and profitability.

In line with the portfolio theory of diversification, complex networks such as SNC and LNC allow companies to spread their risks across multiple nodes. This results in greater flexibility, collaboration, and redundancy within the supply chain, which can enhance supply chain resilience. For instance, companies can maintain a portfolio of suppliers and logistics providers that differ in terms of geography, size, and capabilities. By doing so, they can minimize the impact of any disruptions in their supply networks.

In conclusion, the portfolio diversification theory provides a compelling argument for the positive relationship between network complexity and supply chain resilience. By diversifying their supplier and logistics portfolios, companies can enhance their ability to cope with disruptions and maintain their operations. Complex networks such as SNC and LNC offer companies the opportunity to

spread risks across multiple nodes, providing greater flexibility, collaboration, and redundancy within the supply chain.

Also, as indicated by the General Systems theory, supply chains are dynamic rendering the asymmetric nexus with both disruption and resilience. Modern information technology has changed how supply chains are managed. As revealed, the General Systems theory's main objective is to make sure that every part of the system is interconnected. Hence, it can be concluded that supply chain network complexity dimensions of manufacturing firms in Ghana have proven to have asymmetric relationship with SCR and disruption as supported by the General Systems theory, the accident theory and diversification theory. In this manner, the success or failure of a network complexity depends on how it channels through resilience and disruption of the supply chain.

### **5.3. Implications for practice**

Our research fills an important gap in the supply chain literature by examining the dual nature of network complexity and its impact on supply chain outcomes. While earlier studies have touched on this topic, they did not fully consider all aspects of network complexity and resilience, as demonstrated by Chowdhury et al. (2019), Mitra et al. (2017), and Wang et al. (2018). By shedding light on this crucial area and highlighting the practical implications of our findings, we hope to provide a valuable contribution to the field.

Findings from the study divulge that complex supply base enables businesses to use more suppliers following an interruption which enhances their capacity to recover. Supply chain managers such as logistics, procurement and operations managers should coordinate the multiparty entities in the supply chain to efficiently manage the complex supply network and the firm's cumbersome process in procuring materials have a stronger affinity for supply chain resilience rather than inciting disruption. Additionally, it is anticipated that with time, the nature of the connections between the businesses in the supply chain would improve. Jaradat et al. (2017) contend that in order to comprehend and improve the supply chain, experts must look at it from a system viewpoint. To prevent any interruptions and to enhance the flow of people, goods, and services, managers are required to oversee the system. In order for the system to be full and effective, all the parts of the whole had to be placed together (Stacey, 2011).

The results of this study would give managers a thorough grasp of the industry and allow them to efficiently coordinate the various organisational components to attain an improved SCR. Managers would benefit from studying the General Systems theory by knowing how to cope with issues that hamper the system's efficient operation. Systems theory is dynamic and aids in spotting supply chain interruptions. This helps determine whether a complex system requires more resilience strategies or causes more disruption. A more concerted effort needs to be taken by supply chain actors on the dark side of network complexity. This can be ensured through improved resilience strategies energised by complexity in logistics and possibly supply complexity because resilience strategies enjoin companies in regaining lost performance as a result of disruptions (Marcucci et al., 2021; Mubarik et al., 2021; Trabucco & De Giovanni, 2021). Alternatively, the process of customer complexity should be reengineered by managers whilst supply complexity should be observed with caution.

### **5.4. Managerial insights**

Supply chain managers, including logistics, procurement, and operations managers, would greatly benefit from the insights provided by this study. The results demonstrate the importance of managing supply chain complexity to mitigate the risk of disruptions and to enhance the resilience of the supply chain.

The study suggests that effective risk management strategies, such as monitoring and controlling supply chain processes, establishing backup plans, and maintaining strong relationships with

suppliers and customers, can help mitigate the risk of disruptions. Supply chain managers should consider investing in building resilient supply chains by enhancing collaboration, flexibility, and redundancy in their networks.

Moreover, the study highlights the importance of understanding customer needs and behaviors to anticipate potential disruptions and respond effectively when they occur. Supply chain managers should pay close attention to the customer side of their networks and develop a deeper understanding of their customers' needs, preferences, and behaviors.

Finally, the study emphasizes the importance of logistics management in building resilient supply chains. Supply chain managers should focus on optimizing logistics processes and leveraging technology to improve visibility and control over their supply chain networks (Hamidu et al., 2023).

While the insights and recommendations from this study are primarily focused on supply chain managers, other managers across different functions can also benefit from them. For instance, managers in sales and marketing can benefit from the emphasis on understanding customer needs and behaviours. They can leverage this insight to develop more targeted and effective sales and marketing strategies. Finance managers can benefit from the focus on risk management and resilience in supply chains. They can use these insights to develop financial models that take into account potential supply chain disruptions and their impact on the company's financial performance.

Overall, while the study is focused on supply chain management, the insights and recommendations are relevant to other managers across different functions who are involved in managing and mitigating supply chain disruptions and risks. Nonetheless, supply chain managers may provide insights on how to effectively manage supply chain complexity and build resilient supply chains. Suggestions for managers include implementing effective risk management strategies, developing a deeper understanding of customers, and optimizing logistics processes.

## 6. Conclusion

The supply chain networks among manufacturing firms are becoming increasingly complex, and this complexity can have both positive and negative effects on the supply chain. On one hand, increased complexity can result in greater resilience and the ability to withstand disruptions. On the other hand, it can also increase the likelihood of disruptions occurring in the first place. Therefore, in this study, we examined both the positive and negative aspects of supply chain network complexity, focusing on three dimensions: supply complexity (SNC), customer complexity (CNC), and logistics complexity (LNC). The research analysed the susceptibilities of three supply chain resilience (SCR) strategies: collaboration, flexibility, and redundancy. Using PLS-SEM, we explored the dark and bright side of network complexity in driving supply chain disruption (SCD) and resilience. Our findings provide a valuable contribution to the supply chain literature by shedding light on the dual nature of network complexity and its role in shaping supply chain outcomes. Markedly, past research works failed to consider various aspects of network complexity and resilience (see, Chowdhury et al., 2019; Mitra et al., 2017; Wang et al., 2018), the following outcomes were revealed to add to the scant literature.

It was revealed that SNC has a statistically significant positive relationship with SCD and the three dimensions of SCR somewhat in line with the findings of Iftikhar et al. (2022), Wiedmer et al. (2021), and Yin et al. (2022). However, CNC was found to have a positive relationship with SCD as averred by Yin et al. (2022), whereas LNC related with the three resilience strategies as partly posited by Iftikhar et al. (2022). As advocated by Wiedmer et al. (2021), buyers can diversify their supply networks so they have options by keeping a portfolio of suppliers, but the study finds that by diversifying supplier and logistics portfolios, firms can boost their ability to manage disruptions.

The relationships between network complexity dimensions, and disruption and resilience strategies are asymmetric. While SNC has both positive and negative impacts on disruptions and resilience strategies, CNC and LNC are associated with the negative and positive aspects respectively. Resilience strategies are typically required when the supply chain network is complex, which is why SNC and LNC are positively related to resilience strategies. On the other hand, increased complexity due to CNC is associated with supply chain disruptions, as predicted by the normal accident theory. Therefore, a nuanced understanding of the different dimensions of network complexity is crucial in developing effective disruption and resilience strategies. Organizations should develop contingency plans and establish collaborative relationships with their suppliers and customers to enhance their ability to respond to disruptions.

Supply chain managers, including logistics, procurement, and operations managers, play a crucial role in revitalizing the supply chain network and unlocking its potential. One key area for improvement is the logistics network complexity, which should be enhanced to ensure resilient strategies that can minimize disruptions. However, in today's complex and rapidly changing business environment, it is not enough to rely solely on resilience strategies such as collaboration, flexibility, and redundancies. Supply chain managers must also proactively address the challenges posed by customer complexity and continuously monitor supply complexity to achieve the bright side of the supply chain network.

To achieve heightened operational efficiency, supply chain managers should adopt a proactive approach to risk management and invest in advanced technologies such as predictive analytics, real-time tracking, and automated inventory management. By leveraging these tools, supply chain managers can gain greater visibility into the supply chain network and identify potential disruptions before they occur. In summary, supply chain managers should prioritize the improvement of logistics network complexity, as well as the adoption of resilient strategies and advanced technologies to enhance the bright side of the supply chain network and achieve operational excellence.

The study presented here has some limitations that should be addressed in future research. To begin with, future research could investigate the feedback effect from a complex network and how resilience strategies can improve supply chain performance in this context. One possible research question could be: How does the feedback effect of a complex network influence the effectiveness of resilience strategies in mitigating disruptions to supply chain performance? Researchers could adopt a qualitative or quantitative research methodology and use case studies, simulations or mathematical models to explore this relationship. Additionally, researchers could explore how different types of disruptions, such as infrastructure failures, catastrophic events or supply-demand imbalances, impact supply chain performance in a complex network. One potential research question could be: How do the sub-dimensions of supply chain disruption impact network complexity, and what are the implications for resilience strategies? Researchers could use surveys or interviews to collect data and employ statistical or econometric models to analyze the relationships between these variables.

Furthermore, we suggest that future research could explore the moderating or mediating effects of broader contextual factors such as industry-specific factors, cultural differences or technological advancements on the nexus between network complexity, disruption and resilience. One possible research question could be: To what extent do industry-specific factors influence the effectiveness of resilience strategies in mitigating disruptions to supply chain performance in a complex network? Researchers could use a mixed-methods approach that combines quantitative and qualitative data collection and analysis techniques to address this question.

Overall, these suggested areas of research could contribute to a better understanding of supply chain resilience and help organisations develop effective strategies to cope with disruptions in complex networks.



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Data are available upon request

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